AN ATTEMPT TO ESTIMATE THE DIFFUSE COMPONENT OF SOLAR RADIATION ON HORIZONTAL PLANE FROM SATELLITE IMAGES

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Abstract. *This paper presents an attempt for the estimation of the diffuse part of the hourly solar radiation at the ground level using only images of the Earth taken in the 0.4- 11 μm spectral band by the geostatiollary meteorological satellite Meteosat. Once applied to these images, the Heliosat method produces maps of a quantity called the cloud index, which can be related to the clearness index, which in turn provides the hourly global radiation. Two empirical models are presented. The solar elevation is a common input to both models. The first one makes direct use of the cloud index while the second deals with an intermediate quantity, the total nebulosity. A regression relationship is sought between the diffuse component of the hourly solar radiation measured at eleven locations within the network of the French Meteorological Office and the coincident satellite data acquired at Ecole des Mines de Paris during 1984 and 1985. The error (r.m.s.) in the estimation of the hourly diffuse irradiation ranges from 27 Wh/m² to 98 Wh/m² if estimation is based upon the cloud index, and from 28 Wh/m² to 99 Wh/m² with total nebulosity. the relative error (relative r.m.s.) is independent of the solar elevation and is about 38%, for both years and both models.*

Resume. *Ce présent alticle porte sur l'estimation du rayonnement solaire diffus au niveau du sol et ceci à partir des images en provenance du satellite Météosat. La bande spectrale utilisée est le canal "visible" (0,4 - 1,1 μm). A partir des images satellitaires, en utilisant la méthode Heliosat, on détermine un indice d'ennuagement qui est un indicateur du chemin optique parcouru par le rayonnement solaire. Deux modèles empiriques sont utilisés pour estimer le rayonnement diffus horaire instantané. Le premier utilise directement l'indice d'ennuagement alors qlle le second part d'un paramètre intermédiaire (la nébulosité totale). Différentes relatiolls sont établies entre le rayonnement diffus mesuré sur 11 stations situées en France et les paramétres dérivés des images satellitaires (indice d'ennuagelllent, nébulosité totale). Les données traitées portent sur une périodes de deux ans (1984 et 1985). L'erreul- de reconstitution du rayonnement diffus varie de 27 à 98 Wh/m² pour une estimation sur la base de l'indice d'ennuagement et de 28 à 29 Wh/m² pour la nébulosité totale. L'erreul- relative de reconstitution est de 38% et elle est indépendante de la hauteur du soleil, pour les deux années et pour chaque modèle.*

1. Introduction

The geographical distribution of clouds and their brightness now belong to wqell remotely sensed properties of the Earth [1]. Satellite images have been extensively used to compute incident solar radiation at the surface by many researchers [e.g. 2,3] among them, are those working within the Heliosat programme [4]. The goals of this programme, started in 1978; are to design systems for the efficient use of satellite data in the solar meteorology engineering, to produce maps of the solar radiation and to improve the systems in relation to the results and progress in science and technology. In several tests conducted at various locations and in several years, the maps provided by the Heliostat method showed better than 10% agreement between hourly measurements of the global radiation and satellite-derived values [2,5].

The estimation of the direct and diffuse components of the solar radiation is important for solar related applications. This is because each component affects systems in, basically, different ways [6]. Some instruments offer measurements of these components. However, most of the stations in the world only provide global radiation measurements. Therefore adequate models that extrapolate the two components from the global values are needed and have been developed [6,7]. This paper follows a similar model, and presents two attempts to compute the diffuse component from the cloud index provided by the Heliosat method.

Recently Stuhlman *et al.* [8] presented a model using quite similar data to provide maps of the diffuse component This model makes use of climatological data bases, namely of ozone content, relative humidity, visibility, and also of typical atmospheric profiles of pressure, temperature and water vapour. Its use is limited to large areas (resolution is 50 km) and to monthly means. It yields good results with a precision (r.m.s.) close to 10%. The work of Stuhlmann *el al.* [8] complements a basic model of [9] for the retrieval of the global radiation from Meteosat images, which has been shown to be quite similar in essence to the Heliostat method [2]. Therefore, similar results should be attained if climatological data bases are introduced into the Heliostat method. Some aspects in solar energy engineering may be greatly improved if accurate estimates of the instantaneous diffuse component of solar radiation can be made. For example, the command and control of complex photovoltaic system connected to utility networks. Hence, we focus our attention to the retrieval of such quantities. This paper does not deal with monthly mean, but with instantaneous diffuse radiation.

2. The diffuse component of the solar radiation

Because of the various processes occurring in the atmosphere; such as scattering by molecules clouds and aerosols, and gaseous absorption [9,11], the solar irradiance measured at ground level, G, is composed of a direct solar irradiance, I, and of a diffuse solar irradiance, D. The summation of I and D gives the global solar irradiance G on a horizontal plane at ground level. If the solar irradiance at ground level is known, the direct irradiance can be computed from the unique knowledge of the diffuse irradiance and vise versa. Parameters are used here to describe the atmosphere to a first approximation are; cloud index, n, and nebulosity, N. Units and symbols follow the recommendations of Dogniaux *et al.* [12]

The Heliosat method for the mapping of global radiation at ground level from satellite images has been extensively discussed [2,5,13,14] and will only be presented briefly. The satellite data are normalised to the irradiance which would be measured in the same spectral window on an horizontal plane located at the same pixel under very clear sky. This normalisation is, in a first approximation, equivalent to the computation of an apparent albedo of the ground under clear skies. Moussu *et al.* [13] fully described the clear-sky model presently used in the Heliosat method. The occurrence of a cloud in the field of view of the satellite sensor usually results in an increase of the apparent albedo This increase has been evaluated by Cano *et al* [14] relative to the ground albedo under clear sky and a tropical albedo value for thick and highly reflective clouds. They defined the cloud index, n, at pixel (i,j) and at instant t as the following quantity:

$$n^t(i,j) = \frac{\{\rho^t(i,j) - \rho(i,j)\}}{\{\rho c - \rho g(i,)\}} \qquad 1$$

where: $p^t(i,j)$ is the apparent albedo at pixel (i,j) and at instant t, $\rho g(i,j)$ is the ground albedo under clear-sky, ρc is a typical value of the maximum albedo value clouds.

Due to its very definition, values of *n* greater than 1 can be observed for very reflective clouds.

Numerous comparisons with ground-based measurements [4,5,14] showed that the cloud index is linearly related to the clearness index K_T, defined as the ratio of G to the extraterrestrial irradiance on a horizontal surface on day j, G_{oj}.

The nebulosity (cloud amount), N, represents the fraction of the sky covered by clouds as seen by an observer at ground level [15]. This quantity is defined in oktas (8 classes) or in tenths (10 classes). Nebulosity can be partial; that is, relative to the line of sight, and to cloud types and height. It is called total when all the clouds are taken into consideration without distinction of height or type. The nebulosity has been used in some studies which yielded good results [16,17]. Because the satellite data, under concern, do not provide sufficiently accurate cloud type and top height, the present work only deals with total nebulosity. This parameter can be estimated from the cloud index according to an idea of Perrin de Brichambaut [18]. Using the results of Lund *et al.* [19], about the probability of seeing the blue sky from the ground as a function of solar elevation, y, and total nebulosity, and assuming that this probability is equal to the probability to see the ground through the atmosphere from satellite, Perrin de Brichambaut proposed the following relationship between n and N:

$$N = \frac{n}{[1 - 0.625(1-n)\sin\gamma_{sat}(2.2 - \sin\gamma_{sat}]} \qquad 2$$

where γ is the satellite elevation angle above horizon. Because *n is* a mixture of the cloud coverage and of the cloud optical thickness, this equation is only an approximation of the actual relation, if any. This approximation improves when the clouds tend to be opaque.

3. The data used

The satellite data used originated from the visible/near infrared channel (4.0 1.1 µm) of the Meteosat satellite. This geostationary satellite is located above the equator at longitude 0° and images the third of Earth every half-hour with a spatial resolution of 2.5 km at satellite nadir. This satellite also disseminates its data to end user's stations in analog or digital formats. This study deals with analog data acquired three times a day (morning, noon, afternoon) during 1984 and 1985 at Ecole des Mines de Paris. The system used for acquisition, data digitisation and processing is fully presented by Wald el *al* [20] and Diabaté *et al.* [21]. Moussu *et al.* [13] discussed the particular aspects of such data for scientific uses with reference to their calibration and stability. The spatial resolution of this data set is 7-8 km for Europe.

Hourly diffuse irradiation (D_h) measurement are daily made at eleven location in France by the French Meteorological Office. These measurements are used to derive a regression relationship between (D_h) and n or N for different solar elevation ,γ. Comparisons between satellite estimates and ground-based measurements of irradiation are difficult because the first type of data is an instantaneous measure of a large geographical area while the later is a time-integrated measure made at a particular location. This location corresponds to a very small portion of a pixel. Few authors do explicitly take into account problem of conciling time-averaged pin-point data, and instantaneous space-average data. The frozen turbulence assumption, which says that the optical characteristics of the atmosphere are uniformly advected by the main flow, could allow a time average to be converted into a space average. However, it is difficult to take into account, the variation of the flow with altitude as well as its anisotropy at each pyranometer location. Hence, for the sake of simplicity, the satellite-derived estimates are averaged within the neighbourhood of the ground station before being compared to the ground measurements. Assuming a mean flow rate of 10 m/s, the pixel size being 7km, the values are averaged in squares containing 5 × 5 pixels. Pinker *et al.* [22] studied the effect of different spatial sampling of satellite observations on retrieved surface solar irradiance using two different resolutions: 8 and 50 km, of interest to the international satellite cloud climatology project (ISCCP). They found that, on the average, the results differed by about 8-9 %. When comparing ground measured irradiances to satellite-derived estimates, it was demonstrated that it is possible at one time to get better agreement with one type of sampling and at other times better agreement with a different sampling.

4. Diffuse irradiation from satellite data

The data are grouped in solar elevation classes, the width of them is 5° for y less than 52° and 10° otherwise. The ratio D_h/G_{oh} of the hourly diffuse irradiation, D_h, to the extraterrestrialhourly irradiation on an horizontal plane, G_{oh}, is plotted as a function of the cloud index (or nebulosity), and by class of solar elevation. Then a regression curve is fitted and the r.m.s.scattering of the data around this curve is computed. For each elevation class, the ratio D_h/G_{oh} can be expressed as a function of the cloud index (Figs.1 and 2) or of the nebulosity (Figs.3 and 4):

$$\frac{D_h}{G_{oh}} = A_1(n - n_o)^2 + B_1 \qquad 3$$

or

$$\frac{D_h}{G_{oh}} = A_2(N - N_o)^2 + B_2 \qquad 4$$

Average results are given for the eleven stations in tables I (year 1984) and 2 (year 1985). The parameter $n_o(\gamma)$ *is* the value of the cloud for which the ratio D_h/G_{oh} reaches its maximum: B_1 As the cloud coverage or optical thickness increases, the relative importance of the diffuse component increases, up to a certain value of the cloud index, $n_o(\gamma)$ beyond which the cloud becomes opaque. For the various classes of the solar elevation, no ranges from 0.07 (12°-17°) to 0.44 (53°-65°) for the year 1984 (Table 1) and from 0.17 to 0.45 for 1985 (Table 2). According to the relationship between n and K_T, the corresponding clearness index ranges from 0.78 to 0.45 and from 0.65 to 0.45, respectively. n_o increases very rapidly for the low solar elevation and reaches a more or less constant value of about 0.4 for 30°. For all the classes of solar elevation merged together (12°-65°), n_o equals 0.38 and 0.42, respectively for 1984 and 1985 (K_T of 0.49 and 0.46). n_o and B_1 increase with γ. This can be partly explained by the fact that, when γ decreases, the optical path through the cloud increases and a lower cloud coverage (or optical thickness) is required for the cloud to become opaque. Similar facts are found for N. As expected, B_1 and B_2 are equal, since both represent the maximum value of the ratio D_h/G_{oh}. For γ greater than 17°, this maximum is almost constant, ranging from 0.26 to 0.30 when γ increases. The values, $(D_h/G_{oh})_{n=0}$, are reached for clear sky. They are similar for the years 1984 and 1985.

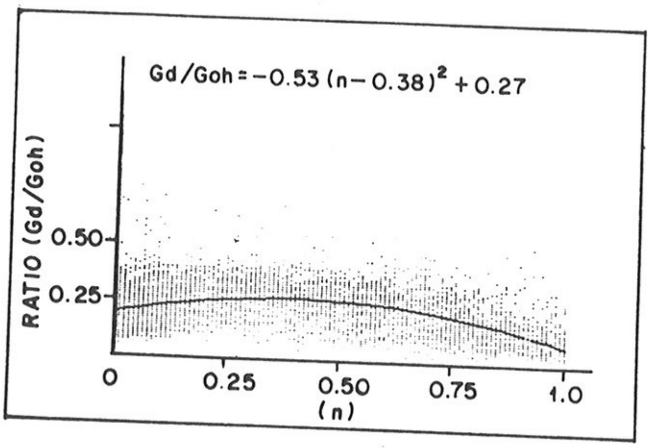

Figure 1: Relationship between the ratio D_h/G_{oh} and the cloud index n, for solar elevations comprised between 12° and 65° for 1984 and the eleven stations. Regression equation is D_h/G_{oh} = -0 53(n - 0. 38)^2 + 0.2 7.

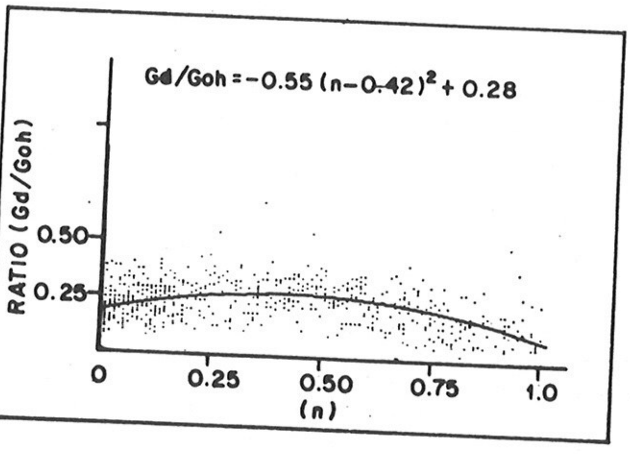

Figure 2: Relationship between the ratio D_h/G_{oh} and the cloud index n, for solar elevations comprised between 38° and 42° for 1984 and the eleven stations. Regression equation is D_h/G_{oh} = -0 55(n - 0.42)^2 + 0.28.

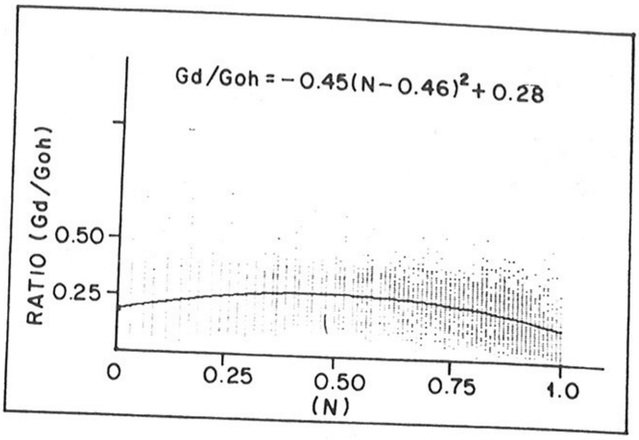

Figure 3: Relationship between the ratio D_h/G_{oh} and the total nebulosity N, for solar elevations comprised between 12° and 65 ° for 1984 and the eleven stations. Regression equation is D_h/G_{oh} = -0.45(N - 0.46)^2 + 0.27

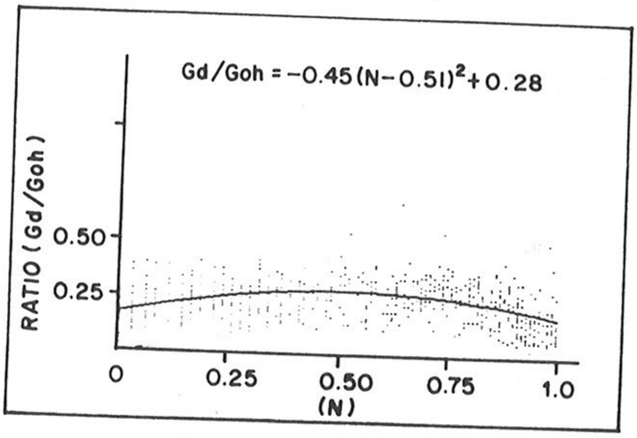

Figure 4: Relationship between the ratio D_h/G_{oh} and the total nebulosity N, for solar elevations comprised between 38° and 42 ° for 1984 and the eleven stations. Regression equation is D_h/G_{oh} = -0.45(N- 0.51)^2 0.28

They decrease slightly from 0.23 when γ increases but can be considered as more or less constant (+10 %) around 0.20 for all solar elevations except at solar Zenith, in accordance with the previous studies of Kimball *et al* (cited in Ivanoff [23]). For all the classes of solar elevation (12°-65°), the ratio $(D_h/G_{oh})_{n=0}$ equals 0.19 and 0.18. The values obtained for $(D_h/G_{oh})_{N=0}$ range from 0.22(12°-17°) to 0.10 (53°-65°) for 1984 and from 0.22 to 0.08 for 1985.

$(D_h/G_{oh})_{N=0}$ can be related to the atmospheric turbidity at least qualitatively. The turbidity is presently considered in the sense of Linke [24], and takes into account the attenuation of the radiation by the aerosols and the atmospheric gases, including water vapour. For clear skies, the greater the turbidity, the greater the ratio $(D_h/G_{oh})_{n=0}$. However, the links between the diffuse component and the turbidity are not very tight. Indeed, the turbidity factor includes all atmospheric extinction processes (scattering, absorption), while the diffuse component depends, only slightly, on the characteristics of absorption phenomena (mainly water vapour).

The error of the regression relationship is expressed as r.m.s. error. When n is dealt with, the r.m.s. increases with ytrom 29 Wh/m^2 (38 % ofthe mean value ofthe ground measurement for γ, ranging from 12° to 17°) to 88 Wh/m^2 (35 %; 53° - 65°) for year 1984. For 1985, the r.m.s. varies from 27 Wh/M^2 for 12°-17° to 98 Wh/m^2 (37 %) for 53° - 65°. One can note that the relative error remains constant, around 38%. When all the classes of solar elevation are merged together (12°-65°), the r.m.s. error ecluals 66 Wh/m^2 and 70 Wh/m^2. As expected, similar results are obtained when considering the nebulosity. The r.m.s. ranges from 28 Wh/m^2 to 89 Wh/m^2 for 1984 and from 34 Wh/m^2 to 99 Wh/m^2 for 1985. For all the classes of solar elevation merged together (12°-65°), the r.m.s. error equals 68 Wh/m^2 and 74 Wh/m^2.

Table 1. Results of the comparisons between the satellite-derived estimates and the ground measurements of D_h. Solar elevations are in degrees and r.m.s. errors in Wh/m^2. Values are for the eleven stations and year 1984.

Solar elevation	A_1	B_1 or B_1	n_o	A_2	N_o	D_h/G_{oh} n=0	D_h/G_{oh} N=0	D_h Wh/m^2	r.m.s.e (n)	r.m.s.e (N)
12-65	-0.53	0.27	0.38	-0.45	0.46	0.19	0.17	175	66	68
12-17	-0.19	0.23	0.07	-0.37	0.32	0.23	0.22	75	29	28
I8-22	-0.42	0.26	0.29	-0.43	0.39	0.22	0.20	101	35	36
23-27	0.46	0.27	0.32	-0.39	0.41	0.22	0.20	129	45	47
28-32	-0.52	0.28	0.37	-0.43	0.15	0.21	0.19	154	53	55
33-37	-0.60	0.29	0.39	-0.53	0.47	0.20	0.18	180	56	57
38-42	-0.55	0.28	0.42	-0.45	0.51	0.18	0.16	191	65	66
43-47	-0.62	0.30	0.41	-0.50	0.49	0.20	0.18	217	75	76
48-52	-0.63	0.29	0.41	-0.47	0.51	0.18	0.17	233	88	89
53-65	-0.78	0.30	0.44	-0.56	0.56	0.15	0.10	252	88	89

Table 2. Results of the comparisons between the satellite-derived estimates and the ground measurements of D_h. Solar elevations are in degrees and r.m.s. errors in Wh/m^2. Values are for the eleven stations and year 1985.

Solar elevation	A_1	B_1 or B_2	n_o	A_2	N_o	D_h/G_{oh} n=0	D_h/G_{oh} N=0	D_h Wh/m^2	r.m.s.e (n)	r.m.s.e (N)
12-65	-0.58	0.28	0.42	-0.51	0.52	0.18	0.14	186	70	74
12-17	-0.21	0.22	0 17	-0.39	0.37	0.23	0.22	72	27	34
18-22	-0.56	0.27	0.43	-0.20	0.55	0.22	0.21	105	39	46
23-27	-0.51	0.28	0.39	-0.47	0.53	0.22	0.14	134	43	52
28-32	-0.58	0.28	0.41	-0.56	0.49	0.21	0.16	159	58	56
33-37	-0.58	0.28	0.44	-0.48	0.55	0.20	0.12	173	59	59
38-42	-0.63	0.28	0.43	-0.56	0.52	0.18	0.13	188	62	62
43-47	-0.57	0.30	0.15	-0.43	0.5I	0.20	0.16	208	75	85
48-52	-0.76	0.30	0.40	-0.65	0.51	0.18	0.14	238	79	88
53-65	-0.70	0.29	0.45	-0.68	0.56	0.15	0.08	260	98	99

5. Conclusion

The r.m.s. error of the regression line between the hourly diffuse irradiation and satellitederived values ranges from 27 Wh/m^2 for total nebulosity. The relative error (relative r.m.s.) is independent of the solar elevation and is about 38% for both years and both models. Considering the high relative error and the analysis of the parameters n_o, B_1, N_o and B_2, the following conclusions may be drawn:

(i) The models are very simple because they are based on one single measurement made by the space-borne sensor within a wide spectral window.

(ii) The solar elevation and the cloud index (or total nebulosity) do not completely determine the diffuse component of the solar radiation at ground level, particularly for clear skies (low value of n or N). Clear sky can be characterized by the atmospheric turbidity. Its influence on diffuse sky radiation is large for n lower than 0.1 (corresponding to clearness index of about 0.7) and becomes less and less important when n increases beyond 0.5 (clearness index of about 0.4).

From these conclusions, the authors are convinced that an efficient model for the retrieval of the diffuse (and direct) hourly radiation from satellite data must comprise a much more detailed description of the radiative processes involved, particularly the scattering by aerosols [25] and absorption by water vapour. An improved model would require information on the spectral intensities of the scattering and absorption processes and hence the use of an appropriate radiometer aboard the satellite. For the time being, the radiometer of the Meteosat satellite does not permit an accurate determination of the atmosphere turbidity because of its poor spectral resolution, except in some particular cases when infrared data can be used for the retrieval of the optical depth of the Saharan dust [26,27]. On the other hand, some satellites such as NOAA, Landsat and Nimbus-7 carry radiometers with more spectral bands and can bring out a satisfying solution to the problem at hand as discussed by Darnell *et al.* [28]. The data of such radiometers, once properly processed, provide knowledge about aerosols [29,30] or about optical properties of the clouds [31-33]. jima. Studies have shown that radiometers including appropriate near infrared spectral band would provide accurate information on the optical properties of the aerosols as well as clouds. The next generation of the NOAA satellites will embark such advanced radiometers in the following years. Improved insights in to radiative transfers within the atmosphere are then expected. Further progress is expected from new radiometers to be flown aboard the next generation of the geostationary satellites such as Meteosat or GOES [36] These satellites will provide images which can be more easily processed in an operational way. The realisation of such easy-to-handle tools [21] will promote the daily use of remote sensing data for solar meteorology or solar energy engineering.

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